AFRL-IF-RS-TR-1999-138
Final Technical Report
June 1999

ROUTING PROTOCOL FOR SMART RADIO AD-HOC NETWORKS

Cornell University

Zygmunt J. Haas

APPROVED FOR PUBLIC RELEASE; DISTRIBUTION UNLIMITED.

AIR FORCE RESEARCH LABORATORY
INFORMATION DIRECTORATE
ROME RESEARCH SITE
ROME, NEW YORK

This report has been reviewed by the Air Force Research Laboratory, Information Directorate, Public Affairs Office (IFOIPA) and is releasable to the National Technical Information Service (NTIS). At NTIS it will be releasable to the general public, including foreign nations.

AFRL-IF-RS-TR-1999-138 has been reviewed and is approved for publication.

APPROVED:

SIAMAK S. TABRIZI
Project Engineer

FOR THE DIRECTOR:

WARREN H. DEBANY, Jr., Technical Advisor
Information Grid Division
Information Directorate

If your address has changed or if you wish to be removed from the Air Force Research Laboratory Rome Research Site mailing list, or if the addressee is no longer employed by your organization, please notify AFRL/IFGC, 525 Brooks Rd, Rome, NY 13441-4505. This will assist us in maintaining a current mailing list.

Do not return copies of this report unless contractual obligations or notices on a specific document require that it be returned.

REPORT DOCUMENTATION PAGE	Form Approved OMB No. 0704-0188

1. AGENCY USE ONLY *(Leave blank)*	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	Jun 99	Final Jul 97 - Dec 98

4. TITLE AND SUBTITLE

ROUTING PROTOCOL FOR SMART RADIO AD-HOC NETWORKS

5. FUNDING NUMBERS

C - F30602-97-C-0133
PE - 62702F
PR - 4519
TA - 42
WU - 99

6. AUTHOR(S)

Zygmunt J. Haas

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

Cornell University
School of Electrical Engineering
323 Frank Rhodes Hall
Ithaca, NY 14853

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

AFRL/IFGC
525 Brooks Rd
Rome, NY 13441-4505

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

AFRL-IF-RS-TR-1999-138

11. SUPPLEMENTARY NOTES

AFRL Project Engineer: Siamak Tabrizi, IFGC, 315-330-4823

12a. DISTRIBUTION AVAILABILITY STATEMENT

Approved for public release; distribution unlimited.

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*

The purpose of this project was to investigate networking aspects of Smart Radio; more specifically, the routing in an ad-hoc networking environment was studied. The Smart Radio principle allows communication using software-generated waveforms. Generation and reception of transmission using such flexible communication is of special interest in the ad-hoc networks environment, because of the unusually difficult communication requirements that such an environment presents. We have proposed and evaluated the performance of a routing scheme that is in particular suitable for ad-hoc networks, due to its mixed nature of on-demand (reactive) and proactive behavior. We have showed that the routing scheme is adaptive in its behavior, and its operational point can be adjusted through sizing of a single parameter - the Zone Radius. The choice of a suitable value of the Zone Radius depends on the "Call-to-Mobility Ratio", which indicates how active a mobile is in initiating traffic and how often the mobile changes its location. Results of our study could be used in designing a new generation of military communication networks, capable of very fast reconfiguration speed, covering large geographical areas, and consisting of a large user population.

14. SUBJECT TERMS

Ad Hoc Networks, Routing Protocols, Reconfigurable Wireless Networks, Zone Routing Protocol, Packet Radio Network, PRNET, Flooding, On-demand Routing, Proactive Routing, Reactive Routing, Quality of Service

15. NUMBER OF PAGES

40

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED	UL

1.0 Table of Contents

1.0	Table of Contents	ii
1.1	List of Figures and tables	iii
1.2	Executive Summary and Recommendations	iv
2.0	Introduction	1
2.1	The Notion of Ad-Hoc Networks	1
2.2	The Communication Environment and the RWN Model	2
2.3	The Challenges of the RWNs	3
2.4	Supporting Ad-Hoc Connectivity – A Historical Look	4
2.5	Routing Protocols – A Short Survey	5
3.0	Routing Protocols for the Reconfigurable Wireless Networks	6
3.1	Reactive vs. Proactive Routing	6
3.2	The Notion of a Routing Zone and Interzone Routing	8
3.3	Interzone Routing and the Zone Routing Protocol	8
3.4	Query Control Mechanisms	9
3.4.1	Loop-back Termination (LT)	10
3.4.2	Query Detection (QD1/QD2)	10
3.4.3	Early Termination (ET)	11
3.4.4	Selective Bordercasting (SBC)	11
4.0	Evaluation of the ZRP Protocol	12
4.1	Performance Results	14
5.0	Discussion and Conclusions	21
6.0	Appendix - Bibliography	22
7.0	Glossary of Acronyms and Notation	26

1.1 List of Figures and Tables

	Title	Page
Figure 1:	Definition of a *Zone Radius*	7
Figure 2:	An Example of IERP Operation	9
Figure 3:	Loop-back Termination	10
Figure 4:	Advanced Query Detection (QD1/QD2)	10
Figure 5:	Early Termination (ET)	11
Figure 6:	Selective Bordercasting (SBC)	12
Figure 7:	IARP Traffic Per m/s	15
Figure 8a:	IERP Traffic Per Route Discovery – Full Bordercasting	15
Figure 8b:	IERP Traffic Per Route Discovery – Selective Bordercasting	15
Figure 8c:	IERP Traffic Per Route Discovery	15
Figure 9a:	Total ZRP Traffic; v=10[m/sec], Rquery=0.1[query/sec] (CMR=10 [query/km])	16
Figure 9b:	Total ZRP Traffic; v=10[m/sec], Rquery=1.0 [query/sec] (CMR=100 [query/km])	17
Figure 9c:	Total ZRP Traffic; v=10[m/sec], Rquery=10.0 [query/sec] (CMR=1000 [query/km])	17
Figure 9d:	Total ZRP Traffic; v=25[m/sec], Rquery=0.1 [query/sec] (CMR=40 [query/km])	17
Figure 9e:	Total ZRP Traffic; v=25[m/sec], Rquery=1.0 [query/sec] (CMR=40 [query/km])	18
Figure 9f:	Total ZRP Traffic; v=25[m/sec], Rquery=10.0 [query/sec] (CMR=400 [query/km])	18
Figure 9g:	Total ZRP Traffic; v=75[m/sec], Rquery=0.1 [query/sec] (CMR=1.3 [query/km])	18
Figure 9h:	Total ZRP Traffic; v=75[m/sec], Rquery=1.0 [query/sec] (CMR=13 [query/km])	19
Figure 9i:	Total ZRP Traffic; v=75[m/sec], Rquery=10.0 [query/sec] (CMR=130 [query/km])	19
Figure 10:	IERP Route Discovery Delay	20
Table 1:	Fixed Simulation Parameters	14
Table 2:	Variable Simulation Parameters	14

1.2 Executive Summary and Recommendations

Executive Summary

The purpose of this project was to investigate networking aspects of Smart Radio; more specifically, the routing in an ad-hoc networking environment was studied. The Smart Radio principle allows communication using software-generated waveforms. Generation and reception of transmission using such flexible communication is of special interest in the ad-hoc networks environment, because of the unusually difficult communication requirements that such an environment presents.

Ad-hoc networks are networks that do not rely on any pre-existing infrastructure. The topology of this type of networks is continuously changing; nodes are mobile and they join and leave the network frequently and without warning. The most prominent example of this type of networks are military networks.

The challenges in the design of ad-hoc networks stem from the fact that there are no central entities in the network. Furthermore, due to the constantly changing network topology, network protocols, such as the routing protocols, have to be extremely efficient.

We have proposed and evaluated the performance of a routing scheme that is in particular suitable for ad-hoc networks, due to its mixed nature of on-demand (reactive) and proactive behavior. The basic idea behind this scheme is to perform flooding; however, the flooding mechanism is in quantum of more than a single hop. This is in contrast with the traditional flooding techniques that exchange the message between any two adjacent nodes. . In our scheme, every node proactively learns its neighborhood and reactively discovers paths by the above-mentioned generalized version of flooding.

We have showed that the routing scheme is adaptive in its behavior, and its operational point can be adjusted through sizing of a single parameter – the Zone Radius. When the Zone Radius is properly chosen, there is a dramatic reduction in the total volume of control traffic. Furthermore, the delay is also reduced. In other words, the Zone Routing Protocol is more efficient and perform better than both, the traditional proactive schemes and the traditional flooding (reactive) schemes. The choice of a suitable value of the Zone Radius depends on the "Call-to-Mobility Ratio," which indicates how active a mobile is in initiating traffic and how often the mobile changes its location.

But flooding, if not controlled properly, can lead to prohibitively large amount of control traffic. In particular, we have examined a number of flood termination techniques, that very efficiently restrict the search performed by the flood to areas that were not previously visited by another tread of the flood. We show the performance of the Zone Routing Protocol for a number of combinations of the flood termination techniques.

Results of our study could be used in designing a new generation of military communication networks, capable of very fast reconfiguration speed, covering large geographical areas, and consisting of a large user population.

Summary of Accomplishments and Results under the Contract

We have performed the following tasks, as identified in the SOW of the F30602-97-C-0133 contract:

- We have examined the various available simulation tools to simulate the performance of our protocols and schemes investigated under this contract. Our conclusion is that, given the nature of the task involved, the best choice was to use the OPNET simulator, in conjunction with our own, in-house written simulations. This conclusion was reached based on the fact that, on one hand, extensive functionality is required to simulate the involved tasks of our work, and, on the other hand, we have already acquired considerable expertise with OPNET simulation. In particular, OPNET provides extensive simulation capabilities, especially as far as the communication and propagation models are concerned. However, OPNET is extremely slow in simulation complex tasks. For example, simulation of a network with 200 nodes may take a couple of days running on Sparc-10 machine! Obviously, this is too slow for any practical purposes.

- Our approach was to use OPNET for studying cases that require its extensive capability. However, when for large simulation tasks, we use our own written simulation. Our simulations are *Event-Driven*, written in C or in C++. Because of the lean code, the execution of our simulation is extremely fast, as compared with other commercial simulators.

- Our models was influenced by the results of the NCASP study, which were provided to us at the beginning of our project.

- We have developed a set of propagation, mobility, and traffic models. These models are being used in our simulation of the Zone Routing Protocols for the Reconfigurable Wireless Networks. In particular, our models include:

➢ Nodal mobility model includes movement of the mobile based on some degree of memory both in the velocity and in the direction. In this sense, our model is different and more practical that the traditional Brownian Motion model. A small number of parameters control the movement of the mobile. Distribution of the parameters allows to investigate the effect of mixture of mobility patterns, as experienced by different mobiles.

➢ Our traffic model is based on either uniform traffic demand or on locality. In the uniform traffic case, communication between any two mobiles is independent of their geographical distance. In the localized model, the probability of communication between two nodes is a non increasing function of the distance between the two nodes. We have experimented with different functions of distance. For example, a stairways type function appears to be of particular interest to military communication in which members of a units have some (nearly equal) probability of communication, but this probability decreases for members of different units. The importance of our models is in the evaluating the sensitivity of our protocols and schemes to the actual distribution of traffic load.

➢ Our propagation model depends on the traditional effects of terrain-dependent exponential attenuation, log-normal long-term shadowing, and non Line-Of-Sight communication.

Using the above simulation tools and simulation models, we have investigated the performance of our routing protocol – the *Zone Routing Protocol* – for its applicability in large (both in span and in the number of nodes) and highly versatile ad-hoc networks. More specifically, given the particular operational conditions, we have evaluated the amount of control traffic, the total overhead, and the delay of the routing operations. We have investigated a number of *flood termination* schemes, which are central to the performance of any on-demand routing protocol. Our results are extremely encouraging, showing a significant decrease in the overall overhead of the routing operation in an ad-hoc network. Of particular interest is the optimal sizing of the *Zone Radius,* which allows to optimize the performance of the network based on its current operational conditions.

Recommendations

In the research performed under this contract, we have investigated the problem of routing in the ad-hoc communication environment. We believe that the proposed here scheme can be well integrated with the design of hardware that is based on the Smart radio principle. However, additional study is required to see how sharing of parameters between the hardware implementation of the radio units and the software implementation of the routing protocol can be exploited. In fact, we believe that a much more extensive study should be conducted in which the issue of parameter sharing among the various protocol layers should be examined. <u>We note here that the use of the proposed control information sharing across the protocol stack will, in particular, allow to utilize the salient features of the Smart Radio technology at higher protocol layers. This is, as opposed to, limiting the benefits of the Smart Radio to the lower layers only.</u>

Additionally, we propose to extend the research effort of this contract to include novel MAC schemes that are of particular interest in the Smart Radio based networks.

Finally, we also recommend that the question of Quality of Service routing in the ad-hoc networking environment be studied. For instance, the following questions should be addressed: how routes should be evaluated and ranked, how a route or a set of routes should be chosen from the set of available routes, how routes should be matched with Quality of Service parameters of traffic flows, and how information should be distributed among the routes. These questions, although posed here in the context of ad-hoc networks, will, most probably, have an impact on the broader field of communication networks.

2.0 Introduction

In the next sections, we introduce the notion of the ad-hoc networks and extend it with our vision of the Reconfigurable Wireless Networks (RWN). In the following chapter number 3.0, we describe our protocol, which we studied in the context of its use with the Smart Radio principle, as part of the work performed under this contract.

2.1. The Notion of Ad-Hoc Networks

An *ad-hoc network* is a network architecture that can be rapidly deployed without relying on pre-existing fixed communication infrastructure. The nodes in a RWN can dynamically join and leave the network, frequently, often without warning, and without disruption to other nodes' communication. Finally, the nodes in the network can be highly mobile, thus rapidly changing the nodal constellation and the presence or absence of links. Examples of the use of the RWNs are:

- tactical operation - for fast establishment of military communication during the deployment of forces in unknown and hostile terrain;
- rescue missions - for communication in areas without adequate wireless coverage;
- national security - for communication in times of national crisis, where the existing communication infrastructure is non-operational due to a natural disaster or a global war;
- law enforcement - for fast establishment of communication infrastructure during law enforcement operations;
- sensor networks - for communication between intelligent sensors (e.g., MEMS[1]) mounted on mobile platforms.

Ad-hoc networks can also find application outside the military/law-enforcement sector. In particular, applications in commercial use for setting up communication in exhibitions, conferences, or sale presentations have been considered. Likewise, in education, ad-hoc networks could be used for operation of wall-free (virtual) classrooms.

Nodes in an ad-hoc network exhibit nomadic behavior by freely migrating within some area, dynamically creating and tearing down associations with other nodes. Groups of nodes that have a common goal can create formations (clusters) and migrate together, similarly to military units on missions or similarly to guided tours on excursions. Nodes can communicate with each other at anytime and without restrictions, except for connectivity limitations and subject to security provisions. Examples of network nodes are soldiers, or unmanned robots. Examples of mobile platforms on which the network nodes might reside are cars, trucks, buses, tanks, trains, planes, helicopters, or ships.

Some of the distinctive attributes of the ad-hoc networks are:

- the network should be instantaneously deployable (and re-deployable) in unknown, arbitrary communication environments;
- radio propagation conditions can differ vastly throughout the network coverage and can constantly change;
- connectivity between adjacent nodes[2] can be intermittent and sporadic, both due to the nodal mobility and due to propagation conditions; and

[1] Micro-Electro-Mechanical-Systems

[2] *Adjacent nodes* are nodes that can communicate directly.

- there may not be any fixed infrastructure present; the mobile nodes are **all** the elements of the network.

In our work on the ad-hoc networks, we have introduced a subclass of these networks, which we termed the *Reconfigurable Wireless Networks (RWN).* The special characteristics of the RWN are:

- the network can be quite large, on the order of hundreds to thousands of nodes; therefore, global algorithms, such as global search procedures, for example, are unsatisfactory;
- the network span can be large as well, ranging from local coverage to metropolitan-size networks;
- the nodes can exist on top of diverse mobility platforms, with quite different mobility patterns, such as speed distribution (including stationary nodes and low-flying planes), changes in the nodal direction of movement, acceleration/deceleration, or restrictions on paths (e.g., a car must drive on a road but a tank does not, a pedestrian is restricted by built objects, an airborne platforms can exist anywhere above some altitude);
- in particular, nodes can move very fast (e.g., airplanes) or be totally stationary[3]; and
- the network must be able to deliver diverse traffic types, ranging from pure voice to integrated voice and image, and even possibly some limited video.

2.2 The Communication Environment and the RWN Model

The following are a number of assumptions about the communication parameters, the network architecture, and the network traffic in our work described here:

- Nodes are equipped with portable communication devices. These may be powered by lightweight batteries. Thus, the transmission range of the devices may be quite limited.
- Connectivity between nodes is **not** a transitive relation; i.e., if node *A* can communicate with node *B* and node *B* can communicate with node *C,* then node *A* **may not,** necessarily, be able to communicate with node *C.* This is referred to as *the hidden terminal problem* [Tobagi85].
- A hierarchy in the network routing and mobility management procedures could improve network performance measures, such as the latency in locating a mobile. However, physical hierarchy may lead to areas of congestion and is very vulnerable to frequent topological reconfigurations.
- We assume that nodes are identified by fixed ID-s (based on IP addresses, for example).
- All the network nodes were created equal; this means that the design of all the nodes is assumed to be identical. However, this does not mean that all the nodes perform exactly the same function within the network. In particular, at some point in time, some nodes may be assigned a specific function in the network.
- Although the network should allow communication between **any** two nodes, it is envisioned that a large portion of the traffic will be between geographically-close nodes; i.e., locality of traffic. This assumption is clearly justified in a hierarchical organization, such as the military. For example, it is much more likely that communication will take place between two soldiers in the same unit, rather than between two soldiers in two different brigades.

---

[3] Rapidly moving platforms require very fast and very efficient protocols

A RWN is a *peer-to-peer* network that allows direct communication between any two nodes, when adequate radio propagation conditions exist between these two nodes and subject to transmission power limitations of the nodes. If there is no direct link between the source and the destination nodes, *multi-hop* routing is used. In multi-hop routing, a packet is forwarded from one node to another, until it reaches the destination. Of course, appropriate routing protocols are necessary to discover routes between the source and the destination, or even to determine the presence or absence of a path to the destination node. Because of the lack of central elements, distributed protocols have to be used.

2.3 The Challenges of the RWNs

The topic of packet radio networks with applicability to ad-hoc networking has recently received increased attention (e.g., [Alwan96], [Bharghavan94], [Dube97], [Fullmer95], [Gerla95], [Karn90], [Lin97], [Scott95], [Toh97]). This interest comes from two different directions – from the military and from the Internet community. Of course, as the communication and networking environment of these two "markets" is quite different, the requirements, and more important the expectations, of what this technology can accomplish are quite different as well. In our work, we address both the military and dual-use applications. In general, we will address in our esearch activity in ad-hoc networks the following three main areas:

- Medium Access Control schemes,
- routing protocols, and
- mobility management.

In this phase of our contractual work, we concentrate mainly on the second aspect only – the routing protocols.

The main challenges in the design and operation of the RWNs stem from:

- the lack of a centralized entity,
- the possibility of rapid platform movements, and
- the fact that all the communication is carried over the wireless medium.

In "regular" cellular wireless networks, there are a number of centralized entities; e.g., the base-stations, the Mobile Switching Centers (MSC-s), and the Home Location Registry. In ad-hoc networks, since there is no preexisting infrastructure, these centralized entities do not exist. The centralized entities in the cellular networks perform the function of coordination. Thus, lack of these entities in the RWNs requires more sophisticated distributed algorithms to perform these functions. In particular, the traditional algorithms for mobility management, which rely on the HLR/VLR[4] and the medium access control schemes, which rely on the base-station/MSC support, cannot be used here.

All communications between all network entities in ad-hoc networks are carried over the wireless medium. Of course, due to the radio communications being extremely vulnerable to propagation impairments, connectivity between network nodes is not guaranteed. In fact, intermittent and sporadic connectivity may be quite common. Additionally, as the wireless

[4] Home Location Registry / Visitor Location Registry

bandwidth is limited, its use should be minimized. Finally, as some of the mobile devices are expected to be hand-held with limited power sources, the required transmission power should be minimized as well. The last two attributes, conservation of wireless spectrum and reduction in transmission power, lead naturally to an architecture in which the transmission radius of each mobile is limited and channels assigned to mobiles are spatially reused. Consequently, since the transmission radius is much smaller than the network span, communication between two nodes may need to be relayed through intermediate nodes; i.e., multi-hop routing is used.

Because of the possibly rapid movement of the nodes and fast changing propagation conditions, network information, such as routing, for example, becomes obsolete quickly. This leads to frequent network reconfigurations and frequent exchanges of control information over the wireless medium. Of course, as the wireless spectrum is at a premium, frequent exchanges of large amounts of data over the air should to be avoided. Moreover, because of the fast changing topology, a large portion of the reconfiguration information will never be used. Thus, the bandwidth used for distribution of the routing update information is wasted. Finally, in spite of these attributes, the design of the RWNs still needs to allow for a high degree of reliability, survivability, availability, and manageability of the network.

2.4 Supporting Ad-Hoc Connectivity – A Historical Look

In 1972, DARPA initiated a research effort to develop the technology for Packet Radio NETwork (PRNET) [Leiner87-2]. The effort was mainly targeted at supporting military communication through the means of sharing a broadcasting radio channel, while supporting some degree of mobility. Although the main application was for military communications, the program stimulated the use of the PRNET technology in many other areas as well ([Flynn86], [Kahn77], [Kleinrock85], [Hajek83]). For example, in airborne mobile radio [Kahn78], [Davies87], [Jubin87], in amateur radio ([Connors83], [Davies87], and [Karn85]) in HF applications (e.g., for the Navy) [Ephremides87], and in satellite communication [Binder87]. The network architecture was a collection of few tens (about 30-50) radio units with relaying (store-and-forward) capability of packets between these units. The network span was relatively small, allowing, in principle, to use one shared access channel.

Although it is unquestionable that the early PRNET efforts provided a solid base for the today's ad-hoc networking activity and its growing interest, the early PRNET-s were mostly oriented at small-to medium-scale networks with limited mobility. The limited network size allowed the use of a single shared channel, which was a relatively common characteristic of these architectures. However, the need for more advanced technology was already then anticipated [Shacham87].

Recent interest in multi-hop radio networking focuses on rapid and unassisted deployment of networks and their self-organizing characteristics ([Haas97-1], [Haas97-2], [Garcia-Luna-Aceves86], [Izumoto93], [Bhatnagar90], [Davis95], [Shor93], [Garcia-Luna-Aceves85], [Lauer88]). Furthermore, the topic of providing ad-hoc connectivity has been introduced by a number of researchers. For example, [Perkins96-1] discusses the use of the Mobile-IP protocol [Perkins96-2] in support of ad-hoc networking. [Johnson96] describes the use of dynamic source routing, which utilizes flooding to discover a route to the destination. [Sharony96] introduces two-layer

architecture of ad-hoc networks. Finally, [Freebersyser96] argues for the use of ad-hoc networking in military applications.

The notion of the RWNs advocated in our work is based on the previous works in this field. However, by introducing this notion, three additional features of ad-hoc communication are emphasized in particular: large network span, large number of users, and highly versatile platforms.

2.5 Routing Protocols – A Short Survey

The wired Internet uses routing protocols based on topological broadcast, such as the OSPF [Moy94]. These protocols are not suitable for the RWN due to the relatively large bandwidth required for update messages.

Routing in multi-hop packet radio networks was based in the past on shortest-path routing algorithms [Leiner87-2], such as Distributed Bellman-Ford (DBF) algorithm [Bertsekas92]. These algorithms suffer from very slow convergence (the "counting to infinity" problem). Besides, DBF-like algorithms incur large update message penalties. Protocols that attempted to cure some of the shortcomings of DBF, such as Destination-Sequenced Distance-Vector Routing (DSDV) [Perkins94], were proposed. However, synchronization and extra processing overhead are common in these protocols. Other protocols that rely on the information from the predecessor of the shortest path solve the slow convergence problem of DBF (e.g., [Cheng89] and [Murthy95]). However, the processing requirements of these protocols may be quite high, because of the way they process the update messages.

An interesting idea of evaluation and selection of different paths for wireless transmission is that of *Least-Resistance Routing* ([Pursley96-1], [Pursley96-2], and [Pursley93]). The Least-Resistance Routing could be very useful in conjunction with the Zone Routing Protocol proposed here.

[Corson95] introduced recently a protocol based a query-reply process. This is an innovative approach. However, practical implementation of this protocol may lead to high communication requirements in the highly versatile RWN communication environment.

[Murthy95] and [Murthy] present a new distance-vector routing protocol for packet radio networks (WRP). Upon a change in the network topology, WRP relies on communicating the change to its neighbors, which effectively propagates throughout the whole network. The salient advantage of WRP is the considerable reduction in the probability of loops in the calculated routes, as compared with other known routing algorithms, such as, for example, DBF. Compared with our routing protocol, the main disadvantage of WRP is in the fact that routing nodes constantly maintain full routing information in each network node, which was obtained at relatively high cost in wireless resources. Our protocol, in contrast, rapidly finds routes, only when transmission is necessary. Moreover, multiple routes are maintained, so that when some of these routes become obsolete, other routes can be immediately utilized. This is especially important when the network contains large number of very fast moving nodes, as is the case in the RWN architecture.

[Sharony96] presents a routing algorithm for ad-hoc peer-to-peer networks, in which each node belongs to two networks: a physical and a virtual network. Routing is based on temporary addresses. A temporary address is a concatenation of the node's address on each one of the two networks. Upon physical migration, a node is required to acquire a new temporary address. In order to communicate with a node, a query phase is initiated by the source, in which the nodes that belong to the source's physical and virtual networks are polled about the address of the destination.

The virtual network routing is an interesting idea. Nevertheless, its practicability appears to be limited, because full connectivity within a physical network is required for the execution of the routing algorithm. It is highly unlikely that in practical situations full connectivity between even geographically close nodes can be guaranteed, mainly because of the hidden terminal problem. Furthermore, the routing can be far from optimal, as it is based on hopping within virtual networks, which are determined by the sources and the destination addresses and not by the nodes' geographical locations.

In contrast, our routing protocol, which is based on the notion of *Routing Zones* and *Route Maintenance Procedure,* incurs very low overhead in route determination. It requires a small amount of routing information to be maintained in each node and the cost in wireless resources for maintaining routing information of inactive routes is limited as well. The protocol identifies multiple routes to the destination (increasing reliability and performance), with no looping problems. However, the most appealing feature of the protocol is that its behavior is adaptive, based on the mobility and calling patterns of the mobile users.

3.0 The Routing Protocol for the Reconfigurable Wireless Networks

We have proposed a novel routing protocol, the *Zone Routing Protocol,* which allows efficient and fast route discovery in the RWN communication environment (i.e., large geographical network size, large number of nodes, fast nodal movement, and frequent topological changes). As part of our work under the current contract, we are investigating the applicability of the *Zone Routing Protocol* in the Smart Radio communication environment. In what follows, we explain the elements of the proposed scheme. However, first, we clarify the difference between *reactive* and *proactive* routing schemes.

3.1 Reactive vs. Proactive Routing

The challenge in designing a routing protocol for the RWNs stems from the fact that, on one hand, to determine a packet route, at least the reachability information[5] of the source's neighbors needs to be known to the source node. On the other hand, in a RWN, this topology may change quite often. Furthermore, as the number of network nodes can be large, the potential number of destinations is also large, requiring large and frequent exchange of data (e.g., routes, routes updates, or routing tables) among the network nodes. Thus, the amount of update traffic is

[5] The reachability information indicates whether a destination node could be reached from the node in question, what is the next neighbor on that path, and what is the "cost" of the path. The "cost" may be based on different criteria, such as, for example, delay, number of hops, or traffic congestion along the path.

quite high. This is in contradiction with the fact that all updates in the wireless communication environment travel over the air and are costly in resources.

The existing routing protocols can be classified either as *proactive* or as *reactive.* Proactive protocols attempt to continuously evaluate the routes within the network, so that when a packet needs to be forwarded, the route is already known and can be immediately used. The family of Distance-Vector protocols is an example of a proactive scheme. Reactive protocols, on the other hand, invoke a route determination procedure on demand only. Thus, when a route is needed, some sort of global search procedure is employed. The classical flooding algorithms are reactive protocols.

The advantage of the proactive schemes is that, once a route is needed, there is little delay until the route is determined. In reactive protocols, because route information may not be available at the time a route request is received, the delay to determine a route can be quite significant. Furthermore, the global search procedure of the reactive protocols requires significant control traffic. Because of this long delay and excessive control traffic, pure reactive routing protocols may not be applicable to real-time communication. However, pure proactive schemes are likewise not appropriate for the RWN environment, as they continuously use a large portion of the network capacity to keep the routing information current. Since in a RWN nodes move quite fast, and as the changes may be more frequent than the route requests, most of this routing information is never even used! This results again in an excessive waste of the network capacity. What is needed is a protocol that, on one hand, initiates the route-determination procedure on-demand, but at limited search cost. Our protocol, the *Zone Routing Protocol (ZRP),* is an example of a hybrid reactive/proactive routing protocol. On one hand, it limits the scope of the proactive procedure only to the node's local neighborhood. On the other hand, the search throughout the network, although it is global, is done by efficiently querying selected nodes in the network, as opposed to querying all the network nodes.

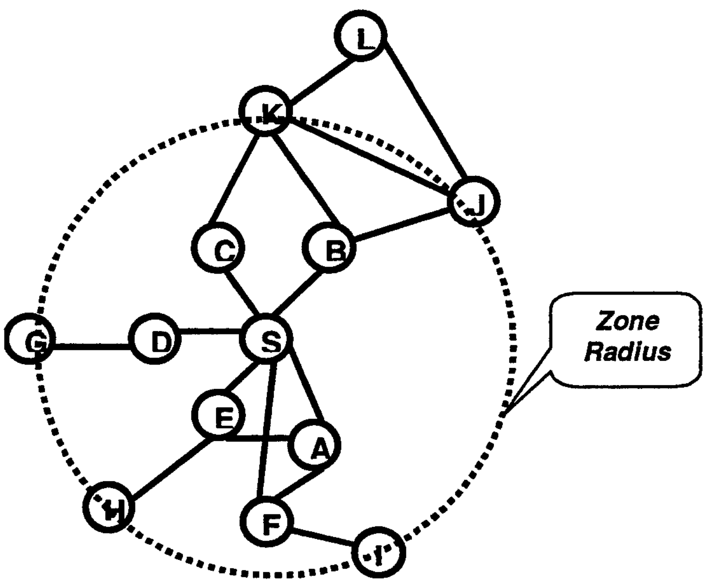

Figure 1: Definition of a *Zone Radius*

A related issue is that of updates in the network topology. For a routing protocol to be efficient, changes in the network topology have to have local effect only. In other words, creation of a new link at one end of the network is an important local event but, most probably, not a significant piece of information at the other end of the network. Proactive protocols tend to distribute such topological changes widely in the network, incurring large costs. The ZRP limits propagation of such information to the neighborhood of the change only, thus limiting the cost of topological updates. The ZRP protocol is based the notion of a *Routing Zone,* which we introduce next.

3.2 The Notion of a Routing Zone and Intrazone Routing

A *routing zone* is defined for each node and includes the nodes whose minimum distance in hops from the node in question is at most some predefined number, which is referred to here as the *zone radius.* An example of a routing zone (for node *S*) of radius 2 is shown in Figure 1.

Note that in this example nodes A through K are within the routing zone of S. Node *L* is outside *S*'s routing zone. *Peripheral nodes* are nodes whose minimum distance to the node in question is equal exactly to the zone radius. Thus, in Figure 1, nodes G-K are peripheral nodes. Zones of different nodes overlap heavily.

Related to the definition of a zone is the coverage of a node's transmitter, which is the set of nodes that are in direct communication with the node in question. These nodes are referred to as *neighbors.* The transmitter's coverage depends on the propagation conditions, on the transmitter power, and on the receiver sensitivity. In our simulation, we define conceptually a radius, d_{xmit}, which is the maximal distance that a node's transmission will be received without errors. Of course, it is important that each node be connected to at least one other node. However, more is not, necessarily, better. As the transmitter's coverage include all the nodes with distance 1 hop from the node in question, the larger the d_{xmit} is, the larger is the content of its routing zone. A large routing zone requires large amount of update traffic.

For the purpose of simplification, we will depict a node's zone as a circle around the node. However, one should keep in mind that the zone is not a description of distance, but rather nodal connectivity (hops).

Each node is assumed to learn the identity of and the (minimal) distance to all the nodes in its routing zone. And conversely, each node needs to learn the distances to the nodes within its zone only. Thus, nodes are updated about topological changes only within their routing zone. Consequently, in spite of the fact that a network can be quite large, the updates are only locally propagated. We assume that the protocol through which a node learns its zone is some sort of a proactive scheme, which we refer to here as the *IntrAzone Routing Protocol (IARP).* In our work, we use a modification of the Distance Vector algorithm. However, any other proactive scheme would do. Of course, in principle, the performance of the ZRP depends on the choice of IARP. However, our experience suggests that the tradeoffs are not strongly affected by the particular choice of the proactive scheme used.

3.3 Interzone Routing and the Zone Routing Protocol

IARP finds routes within a zone. The *IntErzone Routing Protocol (IERP),* on the other hand, is responsible for finding routes between nodes located at distances larger than the zone radius. IERP relies on what we call *bordercasting.* Bordercasting is a process by which a node sends a packet to all its peripheral nodes. A node knows the identity of its peripheral nodes by the virtue of the IARP. Bordercasting can (and should) be implemented by multicasting, if multicasting

is supported within the subnet. Alternatively, unicasting the packet to all the peripheral nodes achieves the same goal, albeit at much higher cost in resources.

The IERP operates as follows: The source node first checks whether the destination is within its zone.[6] If so, the path to the destination is known and no further route discovery processing is required. If the destination is not within the source Routing Zone, the source bordercasts a *route request* (which we call simply a *request)* to all its peripheral nodes.[7] Now, in turn, all the peripheral nodes execute the same algorithm: check whether the destination is within their zone. If so, a *route reply* (which we call simply a *reply)* is sent back to the source indicating the route to the destination (more about this in a moment). If not, the peripheral node forwards the query to its peripheral nodes, which, in turn, execute the same procedure. An example of this *Route Discovery* procedure is demonstrated in Figure 2. The source node *S* sends a packet to the destination *D.* To find a route within the network, *S* first checks whether *D* is within its routing zone.[8] If so, *S* knows the route to node *D.* Otherwise, *S* sends a query to all the nodes on the periphery of its zone[9]; that is, to nodes *C, G,* and *H.* Now, in turn, each one of these nodes, after verifying that *D* is not in its routing zone forwards the query to its "peripheral" nodes. In particular, *H* sends the query to *B,* which recognizes *D* as being in its routing zone and responds to the query, indicating the forwarding path: *S-H-B-D.*

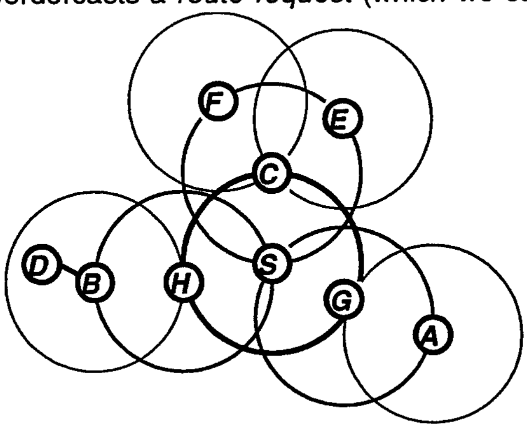

Figure 2: An example of IERP operation

For the purpose of conciseness, we omit here further discussion of the *Zone Routing Protocol.* A more in-depth description of the scheme, as well as the proof that the ZRP does, indeed, find routes between the source and the destination (if such routes exist), is provided in [Haas97-3]. In particular, the important issue of termination of the IERP query process is discussed there, citing few possible alternative approaches.

3.4 Query Control Mechanisms

Because the routing zones heavily overlap, the route query will be forwarded to many network nodes, multiple times. In fact, it is very possible that the query will be forwarded to all the network nodes, effectively flooding the network. But a more disappointing result is that, due to fact that bordercasting involves sending the query over a path of length equal to the zone radius, the

---

[6] Remember that a node knows the identity, distance to, and a route to all the nodes in its zone.

[7] Again, the identity of its zone peripheral nodes are known to the node in question.

[8] Recall that each node knows all the nodes and the routings within its routing zone.

[9] I.e., nodes that are zone-radius away

IERP will result in much more traffic than the flooding itself! What is needed is a more efficient termination criterion than the standard flooding algorithms provide.

In order to understand the cause of the ZRP control traffic problem, it is important to stress one of the key features of the routing zone: A node's response to a route query contains information about that node's entire routing zone. From this perspective, excess route query traffic can be regarded as a result of overlapping query threads (i.e. overlapping queried routing zones). Thus, the design objective of query control mechanisms should be to reduce the amount of route query traffic by steering threads outward from the source's routing zone and away from each other. This problem is addressed from two different perspectives: thread overlap detection/termination and thread overlap prevention.

The standard approach to query thread termination is to discard a thread when it appears at a previously queried node. However, this does not fully exploit the structure of the routing zone. A broader approach is to discard a thread that appears in a previously queried zone. This criterion introduces the first challenge for the design of an effective termination mechanism: How can a previously queried zone be identified when only one node (the central node) was queried?

3.4.1 Loop-back Termination (LT)

It is relatively easy to identify a thread that returns to a routing zone that it previously queried. A node simply examines the accumulated route in the received route query packet to determine if any hop (excluding the most recent hop) lies within its routing zone. If the loop-back condition exists, the thread is discarded. An example of this scheme, which we refer to as Loop-back Termination (LT), is shown in Figure 3. Node S bordercasts a route query to A, which bordercasts it to B, which in turn bordercasts it to C. C terminates the thread (i.e. does not bordercast) because node S, which appears in the accumulated route, also lies within C's routing zone. LT is an ideal mechanism to handle thread loop-back, because the information provided by the accumulated route is sufficient to identify all cases of loop-back.

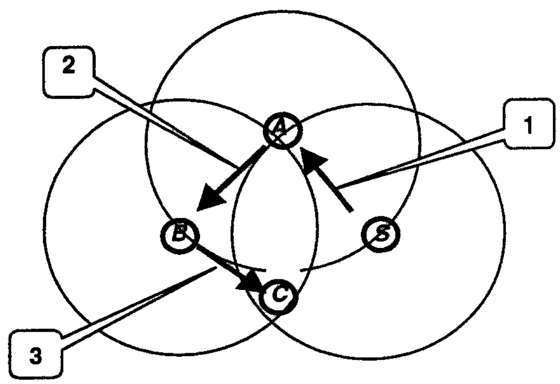

Figure 3: Loop-back Termination (LT)

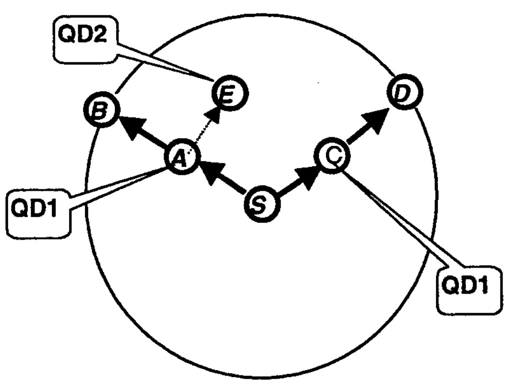

Figure 4: Advanced Query Detection (QD1/QD2)

3.4.2 Query Detection (QD1/QD2)

A majority of thread overlapping occurs by a thread appearing in a zone that was previously queried by another thread. Unlike the loop-back case just described, the ability to terminate in this situation strongly depends on the ability of nodes to detect that a routing zone which they belong to

has been previously queried[10]. Clearly, the central node in the routing zone (which processed the query) is aware that its zone has been queried. In order to notify the remaining routing zone nodes, without introducing additional control traffic, some form of "eavesdropping" needs to be implemented. Based on the ZRP architecture described earlier, it is most convenient to perform query detection at the BRP, which is responsible for query delivery. The first level of Query Detection (QD1), allows the intermediate nodes, which transport queries to the edge of the routing zone, to detect these queries. In single channel networks, it may be possible for queries to be detected by any node within the range of a query-transmitting node. This extended query detection capability (QD2) can be implemented by using IP broadcasts to send route queries[11]. Figure 4 illustrates both levels of advanced query detection. In this example, node S bordercasts to two peripheral nodes, B and D. The intermediate nodes A and C are able to detect passing threads using QD1. If QD2 is implemented, node E will be able to "eavesdrop" on A's transmissions and record the query as well.

3.4.3 Early Termination (ET)

The termination criteria can be further tightened by discarding a thread as it enters a previously queried zone. When the ability to terminate threads is limited to peripheral nodes, threads are allowed to penetrate *into* previously covered areas, generating unnecessary control traffic. This excess traffic can be eliminated by extending the thread termination capability to the intermediate nodes that transport the thread. We refer to this approach as Early Termination (ET). Figure 5 illustrates the operation of the ET mechanism. Node S bordercasts a route query, with node C as one of the intended recipients. Intermediate node A passes along the query to B. Instead of delivering the query to node C, node B terminates the thread because a different thread of this query was previously detected. It should be noted that ET only allows partial participation of intermediate nodes in the route query process. Intermediate nodes are restricted from issuing new queries. Otherwise, the ZRP would degenerate into a flooding protocol.

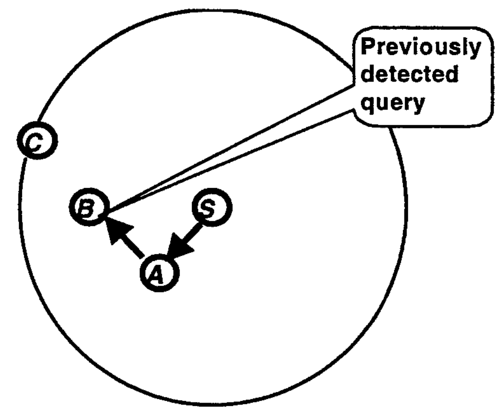

Figure 5: Early Termination (ET)

3.4.4 Selective Bordercasting (SBC)

We now address the more complicated issue of thread overlap prevention. By concentrating on the elimination of overlap locally, some degree of control can be imposed on the direction of thread propagation, thereby reducing thread overlap farther out in the network. Local

[10] The ID of the node that bordercasted the first detected query thread is also recorded. In order to ensure full network coverage for that query, future threads received from that bordercasting node are not automatically discarded.

[11] Alternatively, IP can unicast the queries if the MAC and IP layers are permitted to operate in promiscuous mode.

thread overlap is due to the heavy overlap of peripheral nodes' routing zones, especially as the routing zone radius increases. Rather than bordercast queries to all peripheral nodes, the same coverage can be provided by bordercasting to a properly chosen subset of peripheral nodes, through a mechanism that we term Selective Bordercasting (SBC).

SBC requires that the IARP provides network topology information for an extended zone that is twice the radius of the routing zone. Prior to bordercasting, a node first determines the subset of outer peripheral nodes[12] covered by its assigned inner peripheral nodes. The node then bordercasts to a subset of the assigned inner peripheral nodes which form a "minimal" partitioning set of the outer peripheral nodes. Figure 6 provides an illustrative example of a SBC application. Node S's inner peripheral nodes are A, B and C. Node S's outer peripheral nodes are F, G, H, X, Y and Z. We can see from the overlapping routing zones that the two inner peripheral nodes of node B (H and X) are also inner peripheral nodes of A and C. Consequently, node S can choose to eliminate node B from its list of bordercast recipients. Node A can provide coverage to F, G and H, and node C can cover X,Y and Z. In this way, we are able to provide full coverage over the extended zone while preventing overlapping queries.

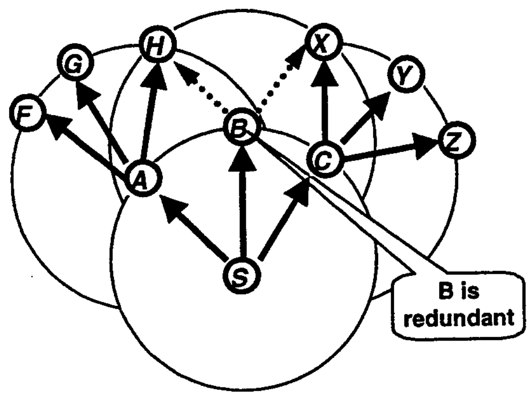

Figure 6: Selective Bordercasting (SBC)

The proposed technique for computing this minimal partitioning set is based on the "greedy" heuristic introduced in [Johnson74]. Each of the selected inner peripheral nodes is sent a list (in the route query packet) of the outer peripheral nodes that it partitions. This list becomes the recipient node's set of assigned inner peripheral nodes. The restriction imposed on the set of inner peripheral nodes helps to direct query threads outward from the source, rather than overlap or loop back on themselves.

Unlike the other query control techniques, SBC does not come for free. The amount of IARP traffic increases to provide extended zone topology. In addition, the length of each IERP route query packet increases in order to accommodate the list of assigned peripheral nodes. To be viable, this added cost must be offset by the reduction in query packet transmissions due to overlap prevention.

4.0 Evaluation of the ZRP Protocol

The performance of the ZRP was evaluated based on simulations of 500 node ad-hoc networks, over a range of routing zone radii (ρ), from purely reactive routing (ρ=1 hop) to purely proactive routing ($\rho \rightarrow \infty$ hops). Performance was gauged by measuring the control traffic generated by the ZRP and the average response time of the reactive route discovery process.

Measurements of control traffic is reported in terms of ID fields (rather than packets) transmitted at the network layer. This distinction allows us to account for the variable length of the IERP control packets due to factors such as route accumulation. The overall ZRP control traffic is

[12] For the purpose of this discussion, we will refer to the peripheral nodes of the *routing zone* as *inner* peripheral nodes and the peripheral nodes of the *extended zone* as *outer* peripheral nodes.

viewed as the sum of the ID fields in the transmitted intrazone update packets and the interzone route request/reply packets. The neighbor discovery beacons are excluded from our measurement of ZRP control traffic because we assume that this service is already provided in conjunction with the MAC protocol.

The delay performance of the ZRP is reflected by the average delay of an IERP route discovery (delay between the time that a route query packet is issued and the first route response packet is received). Like our measurements of control traffic, we generalize the delay performance by expressing it in terms of the transmission delay of an ID field.

Our simulated network consists of 500 mobile nodes, whose initial positions are chosen from a uniform random distribution over an area of 1500 [m] by 1500 [m]. All nodes move at a constant speed, v, with an initial direction,[13] θ, which is uniformly distributed between 0 and 2π. When a node reaches the edge of the simulation region, it is reflected back into the coverage area, by setting its direction to $-\theta$ (vertical edges) or $\pi-\theta$ (horizontal edges). The magnitude of the velocity is not altered.

For the purposes of our simulation, we assume that there is no MAC layer channel contention. This assumption prevents the ZRP delay measurements from being biased by the delays associated with any particular MAC collision avoidance scheme.

Our assumption of a collision-free media access protocol means that the average SIR of a received packet is limited by the ambient background noise and receiver noise. For fixed transmitter and noise powers, we assume that the BER is reasonably low within a distance, which we call d_{xmit}. Beyond d_{xmit}, the BER increases rapidly. This behavior results from a rapid decrease in received power as the separation distance is increased. We approximate this rapid increase in BER by the following simplified path loss model:

$$PL(d)=\begin{cases} 0\ [\mathrm{dB}] & \text{for} \quad d \le d_{xmit} \\ \infty\ [\mathrm{dB}] & \text{for} \quad d > d_{xmit} \end{cases}$$

We interpret this behavior as follows: any packet can be received, error-free, within a radius of d_{xmit} from the transmitter, but is lost beyond d_{xmit}. Since packet delivery is guaranteed to any destination in the range of the source, we are able to further reduce the complexity of our model by eliminating packet retransmission at the data link level.

To accommodate the heavy computational load of simulating a 500 node ad-hoc network, the IARP and IERP are simulated separately. The OPNET™ Network Simulator from MIL3, an event driven simulation package, is used to evaluate the performance of the IARP over a range of routing zone radii. The IARP simulations were run for a duration of 125 seconds. No data was collected for the first 5 seconds of the simulations to avoid measurements during the transient period and to ensure that the initial intrazone route discovery process stabilizes.

The simulation of the IERP is based on the assumption that the network topology remains constant over the duration of a route discovery[14]. IERP performance measurements are gathered from 2500 route discoveries performed over a total of 50 independent "snapshots" (fixed network

[13] Direction is measured as an angle relative to the positive x-axis.

[14] The short range radios (d_{xmit} = 0.1 km) are assumed to support transmission rates on the order of at least 100 kbps, resulting in short query transmission delays. This makes our short-term fixed topology assumption reasonable.

configurations) of our network. Each route query is for a destination selected from a uniform random distribution of all nodes outside of the querying node's routing zone. These route queries represent both the initial query performed at the beginning of a session and subsequent queries due to reported route failures.

We assume the average network load to be low. Thus, the queueing delays experienced by route queries are solely due to the bordercasting of a single route query. This assumption is reasonable if the query packets form a separate queue from the actual traffic queue or if they are given a higher transmission priority. We further assume that propagation and node processing delays are negligible.

Parameter	Symbol	Value
Network coverage area	A	1500 [m] x 1500 [m]
Transmission radius	d_{xmit}	100 [m]
Beacon period	T_{beacon}	0.2 [sec]
Transmission rate	R_{xmit}	1.0 [Mbps]

Table 1: Fixed Simulation Parameters

Parameter	Symbol	Values
Routing zone radius	ρ	1-10 [hops]
Node speed	v	10-75 [m/sec]
Mean route query rate	R_{query}	0.1-10.0 [query/s/node]

Table 2: Variable Simulation Parameters

4.1 Performance Results

Results of our simulation are presented in the following figures. Figure 7 demonstrates the dependence of intrazone control packets on the routing zone radius, ρ, for various rates of network reconfiguration. A distinction is made between the full bordercasting and selective bordercasting schemes because the selective bordercasting requires the IARP to maintain an extended zone of radius 2ρ. The increase in IARP traffic resulting from the extended routing zone is shown to be quite significant. In both cases, the amount of IARP control traffic *per node* is approximately proportional to ρ^2. This behavior is to be expected, since the amount of proactive routing traffic *per node* is proportional to the number of nodes that are being "tracked" in the routing zone, and the number of zone nodes is proportional to the "area" ρ^2) of the zone. It should be noted that there is no intrazone control overhead for ρ=1. All nodes within a routing zone of ρ=1 are, by definition, neighbors. Consequently, the Neighbor Discovery Protocol provides all of the information needed to maintain connectivity within the routing zone.

We examine the behavior of the IERP control traffic by first focusing on the full bordercasting and selective bordercasting cases separately. Figure 8a shows the performance of the query detection/termination techniques that are *effective* in controlling the propagation of IERP traffic in conjunction with full bordercasting. To be considered effective, we require that the

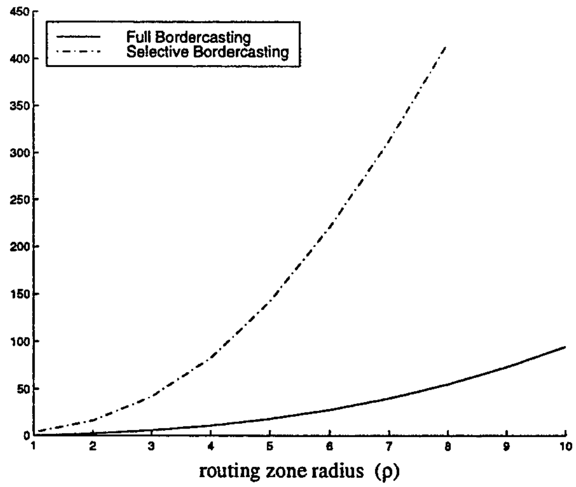

Figure 7: IARP Traffic Per m/s

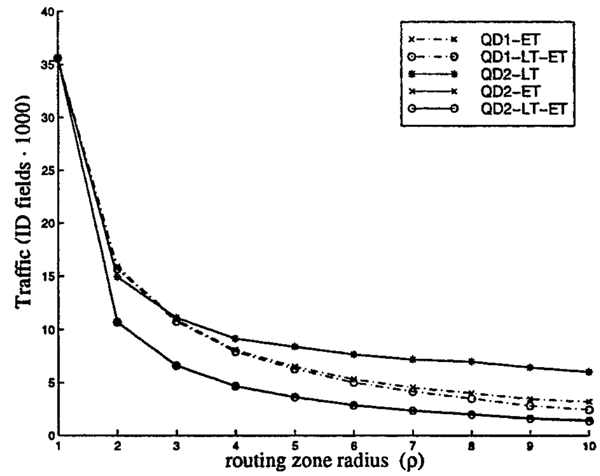

Figure 8a: IERP Traffic Per Route Discovery -- Full Bordercasting

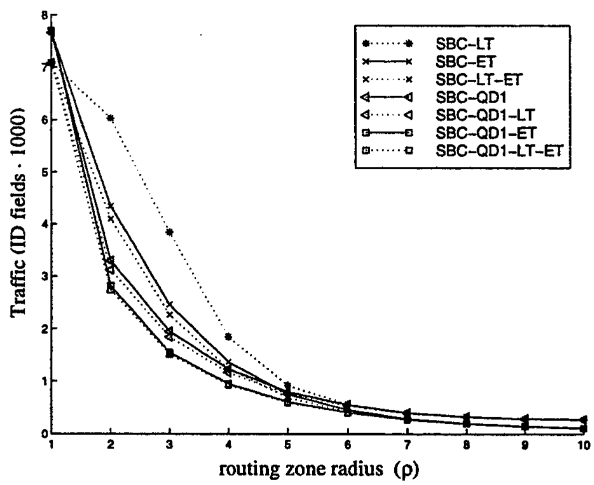

Figure 8b: IERP Traffic Per Route Discovery -- Selective Bordercasting

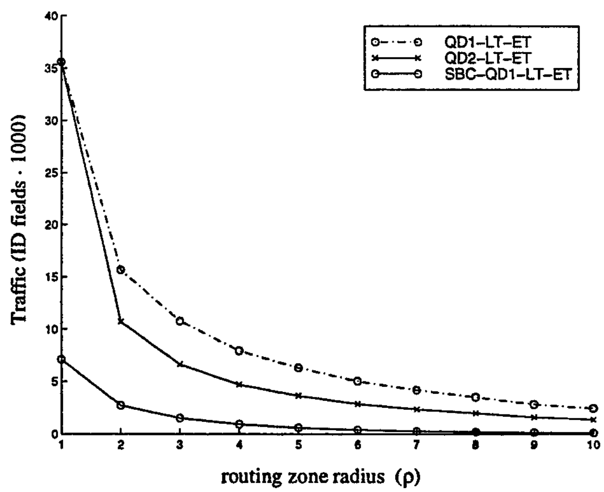

Figure 8c: IERP Traffic Per Route Discovery

amount of IERP traffic per route discovery be a decreasing function of the routing zone radius. We note that some form of advanced query detection (either QD1 or QD2) is needed to properly contain the spread of query packets. Single channel networks, which can implement QD2, may experience approximately 40% less reactive route discovery traffic than those networks that only implement QD1. Early termination (ET), although not "effective" by itself, provides a significant reduction in the amount of IERP traffic when used in combination with the other techniques. As we would expect, the amount of IERP traffic decreases as the query detection capabilities are extended and the termination criteria become stronger. Note the significant boost in performance compared with traditional flooding algorithms (ρ=1).

The performance of selective bordercasting is reflected in Figure 8b. The local overlap prevention provided through selective bordercasting is strong enough to be effective when used in conjunction with *any* combination of LT, ET and QD1. We note the absence of QD2, which proved to be a powerful query control technique when used with full bordercasting. It was discovered that the combination of QD2 and selective bordercasting prevented the IERP route discovery process from achieving full network coverage. This incompatibility occurs because nodes that detect, but do not propagate, *selectively* bordercasted queries, do not necessarily fall under the coverage of the query (due to the focused coverage of a selective bordercast, as compared to the omni-directional coverage of a full bordercast).

Because the LT, ET and QD1/QD2 techniques can be implemented with no additional traffic and negligible computational overhead, the full array of *valid* query control techniques should be applied to provide the best IERP traffic performance. [15]

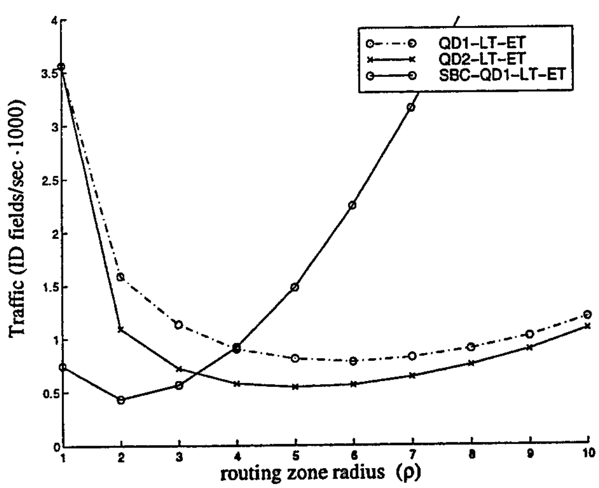

Figure 9a: Total ZRP Traffic
v = 10 [m/sec], R_{query} = 0.1 [query/sec] (CMR=10 [query/km])

Figure 8c clearly demonstrates the extent to which the proposed query control mechanisms suppress redundant query traffic. As stated earlier, in the absence of an effective query control strategy, the amount of reactive traffic will increase with the size of the routing zone. When none of the proposed query control schemes are employed, we observe that the amount of query traffic increases linearly with the routing zone radius. For ρ = 3, for example, the IERP without query control generates about twice as much traffic as flooding, and about 10 – 50 times as much traffic as the most effective query control mechanisms.

Figure 8c also provides a direct comparison between the best IERP traffic performance available from the full and selective bordercasting implementations. All else being equal, selective bordercasting

[15] Recall that QD2 is not supported by networks which use multiple channels or IERP implementations that use selective bordercasting

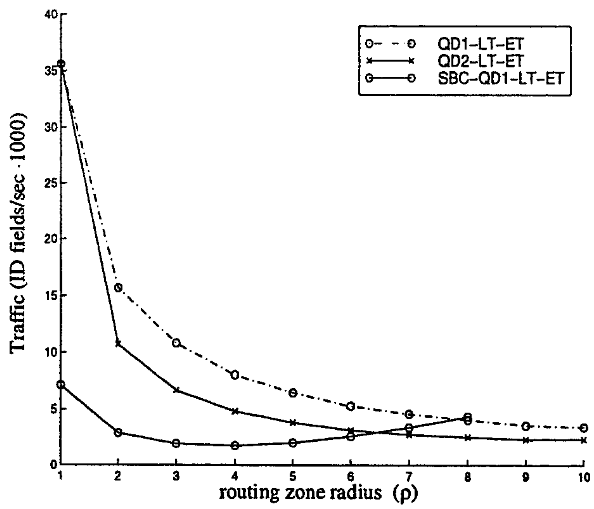

Figure 9b: Total ZRP Traffic
v = 10 [m/sec], R_{query} = 1.0 [query/sec] (CMR=100 [query/km])

Having analyzed the behavior of the individual IARP and IERP components, we now focus our attention on the total ZRP control

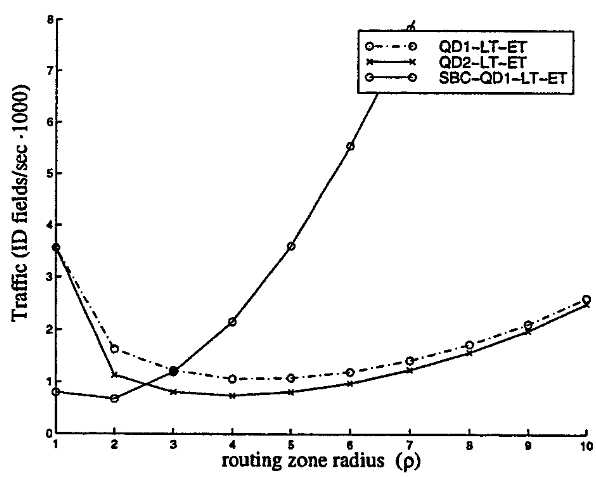

Figure 9d: Total ZRP Traffic
v = 25 [m/sec], R_{query} = 0.1 [query/sec] (CMR=4 [query/km])

provides a substantial reduction in IERP traffic compared with full bordercasting. In the case of flooding (ρ=1), selective bordercasting generates approximately 20% of the full bordercasting traffic. The impact is even more significant as the routing zone radius increases.

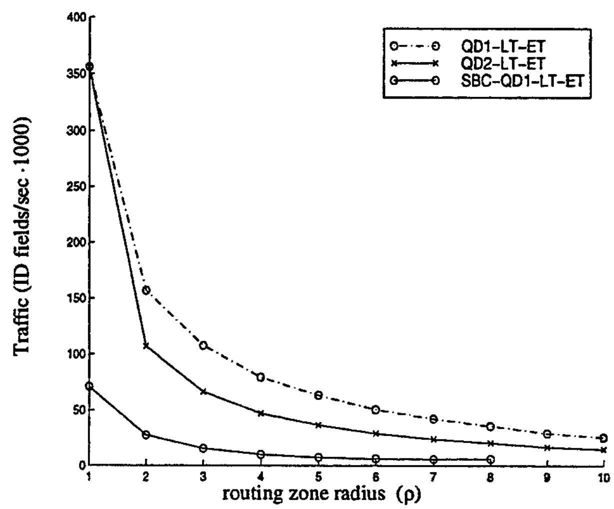

Figure 9c: Total ZRP Traffic
v = 10 [m/sec], R_{query} = 10.0 [query/sec] (CMR=1000 [query/km])

traffic. Figures 9 a-i show how the ZRP can be optimized for different conditions of node mobility and call activity, through the adjustment of the routing zone radius. Keeping the route query rate fixed, we see that the optimal routing zone radius decreases as nodal velocity increases. Increased nodal velocity causes the network to reconfigure more rapidly, resulting in an increased of IARP route update traffic. Likewise, we find that, for a constantnode velocity, the optimal routing zone radius increases with the route query rate. Increased call activity results in the generation of additional IERP route query traffic, but has no effect on the reconfiguration rate of the network (i.e. no effect on the IARP traffic). We summarize

these trends as follows: increased CMR[16] favors a more proactive ZRP configuration (larger routing zones). Likewise, decreased CMR favors a more reactive ZRP configuration (smaller routing zones).

Comparing selective bordercasting with full bordercasting, we find that the selective bordercasting implementation favors a more reactive ZRP configuration. This is to be expected, since selective bordercasting was shown to improve the efficiency of the reactive IERP, while adding significant cost to the proactive IARP. In single channel networks, the best full bordercasting solution appears comparable to the best selective bordercasting approach. In multi-channel networks, where QD2 may not be employed,

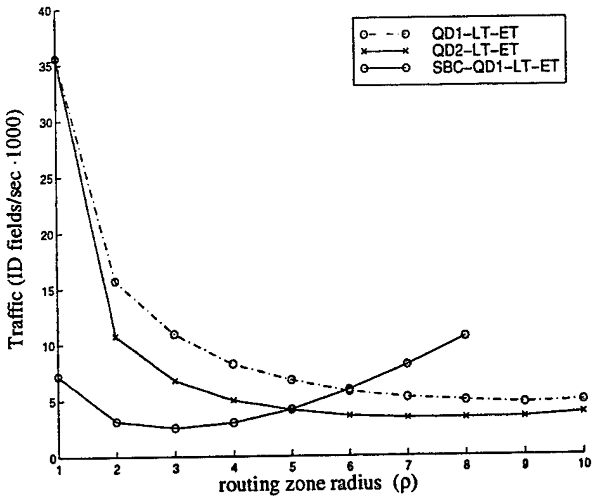

Figure 9e: Total ZRP Traffic

v = 25 [m/sec], R_{query} = 1.0 [query/sec] (CMR=40 [query/km])

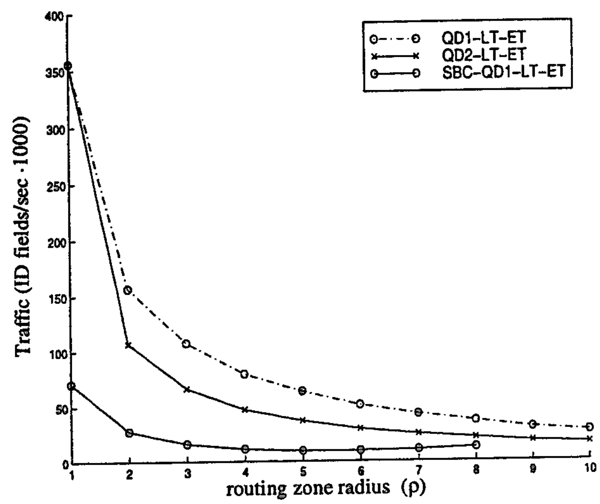

Figure 9f: Total ZRP Control Traffic

v = 25 [m/sec], R_{query} = 10.0 [query/sec] (CMR=400 [query/km])

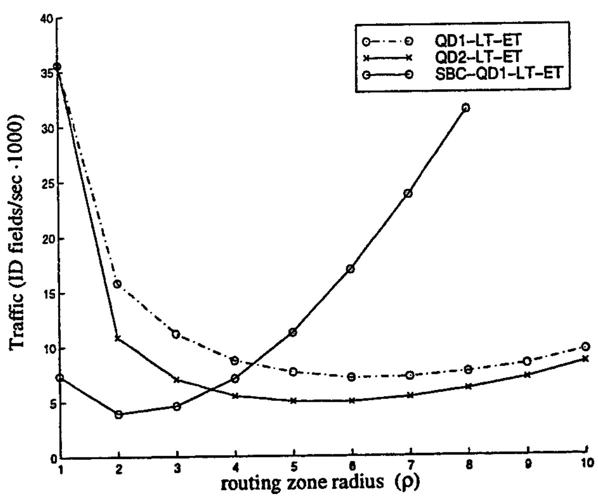

Figure 9g: Total ZRP Traffic

v = 75 [m/sec], R_{query} = 0.1 [query/sec] (CMR=1.3 [query/km])

---

[16] Call-to-mobility ratio. Increased CMR corresponds to increased route query rate or decreased node mobility. Likewise, decreased CMR corresponds to either decreased route query rate or increased node mobility.

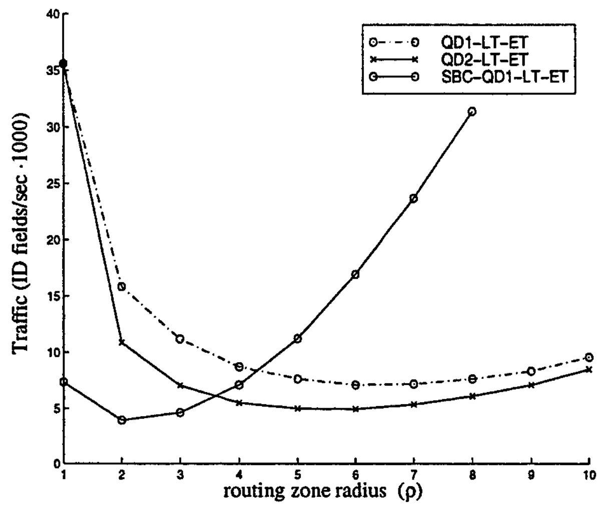

Figure 9h: Total ZRP Control Traffic
v = 75 [m/sec], R_{query} = 1.0 [query/sec] (CMR=13 [query/km])

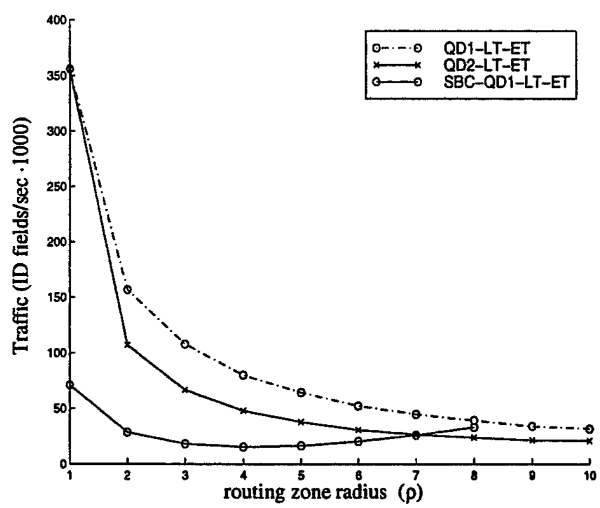

Figure 9i: Total ZRP Control Traffic
v = 75 [m/sec], R_{query} = 10.0 [query/sec] (CMR=130 [query/km])

selective bordercasting may result in about 50% as much traffic as a full bordercasting approach.

We also gauge the performance of the ZRP in terms of route discovery delay. Figure 10 shows that the route discovery delay, like the IERP control traffic, is a decreasing function of the routing zone radius. This relationship is essentially influenced by the same factors that govern the IERP traffic behavior. First, packet transmission time is reduced due to the shorter length of accumulated routes for larger routing zone radii. Second, each query experiences fewer IERP queuing delays due to the increased separation distance between peripheral nodes.

Selective bordercasting schemes exhibit better delay performance than full bordercasting schemes for low routing zone radii, but slightly worse delay performance for larger routing zone radii. At low routing zone radii, selective bordercasting benefits from the reduced queueing delay at each peripheral node. However, at larger radii, the appended list of assigned inner peripheral nodes may be relatively large, resulting in extra transmission delay that offsets the benefits of the reduced queueing delays.

Rather than compare the route discovery delays of full bordercasting and selective bordercasting for the same routing zone radius, a more meaningful comparison is the delay between full bordercasting and selective bordercasting at their respective optimal routing zone radii. Recalling that selective bordercasting operates at a much lower routing zone radius, we see that full bordercasting can respond to a route query in as little as 1/3 the time as selective bordercasting. Given the assumptions behind our delay model, the relative delay performance of selective bordercasting is somewhat optimistic. If

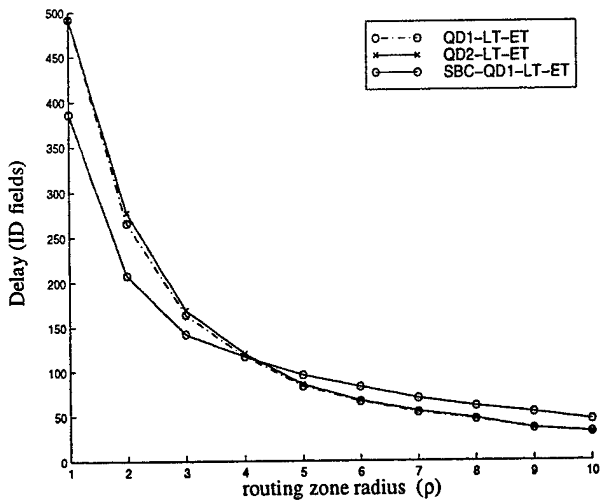

Figure 10: IERP Route Discovery Delay

the queueing delays due to IARP traffic and the processing delays of the query control algorithms are also factored in, the selective bordercasting can be expected to exhibit relatively worse average route discovery delay.

5.0 Discussion and Conclusions

This report is submitted as part of the documentation requirements under the contract number F30602-97-C-0133. An intermediate project report was submitted to the government in January 1997.

The Zone Routing Protocol (ZRP) provides a flexible solution to the challenge of discovering and maintaining routes in a wide variety of ad-hoc network environments. The ZRP combines two radically different methods of routing into one protocol. Intrazone routing uses a proactive protocol to maintain up-to-date routing information to all nodes within its routing zone. By contrast, interzone route discovery is based on a reactive route request/route reply scheme.

The amount of intrazone control traffic required to maintain a routing zone increases with the size of the routing zone. However, the structure of the routing zone can be exploited to significantly reduce the amount of reactive interzone control traffic. Using a mechanism that we refer to as bordercasting, queries may be passed directly to the periphery of the queried routing zone, without incurring any queueing delays at intermediate nodes. An undesirable side effect of bordercasting is the overlapping of query threads. We have introduced and analyzed the advanced query detection and termination techniques (LT, QD1/QD2, ET) which effectively combat the redundant querying, while generating no additional control traffic and requiring negligible computational overhead. Further reduction of the interzone control traffic can be achieved by preventing thread overlap locally through *selective* bordercasting. Unlike the other query control mechanisms, selective bordercasting requires additional overhead, primarily through the proactive maintenance of an extended zone.

For networks characterized by highly mobile nodes and very unstable routes, the hybrid proactive-reactive routing scheme produces less average total ZRP control traffic than purely reactive (ρ=1) or purely proactive ($\rho \rightarrow \infty$) routing. Increasingly reactive ZRP configurations (smaller routing zones) appear to be more suitable for networks that exhibit low call to mobility ratios. On the other hand, networks characterized by slower moving, highly active nodes (frequent route requests), lend themselves to a more proactive configuration (larger routing zones).

Selective bordercasting favors a more reactive ZRP configuration than full bordercasting. For single channel networks, the amount of routing traffic produced through selective bordercasting is comparable to the traffic produced through full bordercasting. For multiple channel networks, however, selective bordercasting produces about half the control traffic as full bordercasting.

We note that for networks with low activity, the instantaneous network load is generally dominated by the control traffic from a single route discovery. Under these conditions, both selective and full bordercasting have been shown to provide noticeably faster route response time than traditional flooding schemes. When the ZRP is configured to minimize total routing control traffic, we find that full bordercasting responds to route queries at least three times faster than a selective bordercasting implementation.

Based on these results, selective bordercasting may be a suitable platform for the IERP in multiple channel networks where conservation of bandwidth is more important than delay performance. In all other cases, it appears that the simpler full bordercasting protocol is the preferred query propagation mechanism.

We have demonstrated that the ZRP may be configured to minimize the amount of routing control traffic, given *a priori* knowledge of the network nodal velocity and route query rate. Recall that the route query rate reflects not only the initial route query for a destination, but also subsequent queries in response to route failure. Thus, the route query rate is not only a function of the communication activity of the node, but is also dependent on node velocity and routing zone radius.

We have publicized some of our results in a number of papers presented at different conferences, as outlined in the following list. Acknowledgement to the AFRL contract was given in these papers.

- Z.J. Haas and S. Tabrizi, "On Some Design Choices in Ad-Hoc Communications," IEEE MILCOM'98, Bedford, MA, October 18-21, 1998
- Z.J. Haas and M.R. Pearlman, "The Performance of Query Control Schemes for te Zone Routing Protocol," ACM SIGCOMM'98
- Z.J. Haas and M.R. Pearlman, "The Zone Routing Protocol (ZRP) for Ad Hoc Networks," Internet Draft, <draft-haas-zone-routing-protocol-01.txt>
- M.R. Pearlman and Z.J. Haas, "The Performance of Zone Routing Protocol in Reconfigurable Wireless Networks," accepted for publication in IEEE JSAC, issue on Ad Hoc Networks.

Under separate two White Papers recently submitted to the AFRL, we propose to extend this effort to include novel MAC schemes that are of particular interest in Smart Radio based networks. Additionally, a new concept of sharing control information across the protocol stack has been advocated in these White Papers. Implementation of this concept will have far-reaching impact of our results. <u>We note here that the use of the proposed control information sharing across the protocol stack will, in particular, allow to utilize the salient features of the Smart Radio technology at higher protocol layers. This is, as opposed to, limiting the benefits of the Smart Radio to the lower layers only.</u> Funding of this proposed works will have a significant impact on our ability to present an <u>integrated</u> framework of our study, which includes the optimization of the Smart Radio based network at multiple protocol layers.

6.0 Appendix - Bibliography

[Alwan96] A. Alwan, R. Bagrodia, N. Bambos, M. Gerla, L. Kleinrock, J. Short, and J. Villasenor, "Adaptive Mobile Multimedia Networks," *IEEE Personal Communications,* pp.34-51, April 1996.

[Bertsekas92] D. Bertsekas and R. Gallager, *Data Networks,* Second Edition, Prentice Hall, Inc., 1992.

[Bharghavan94] V. Bharghavan, A. Demers, S. Shenker, and L. Zhang, "MACAW: A Media Access Protocol for Wireless LANs," in Proc. of *ACM SIGCOMM'94,* pp.212-225, 1994.

[Bhatnagar90] A. Bhatnagar and T.G. Robertazzi, "Layer Net: A New Self-Organizing Network Protocol," IEEE Milcom'90, vol.2, pp.845-849, Monterey, CA, 30 Sept.-3 Oct. 1990.

[Binder87] R. Binder, S.D. Huffman, I. Gurantz, and P.A. Vena, "Cross-link architectures for a multiple satellite system," *Proceedings of the IEEE,* vol.75, pp.74-82, January 1987.

[Connors83] D. Connors, "Amateur packet radio," in *INFOCOM'83,* panel session, April 1983.

[Cheng89] C. Cheng, R. Reley, S.P.R. Kumar, and J.J. Garcia-Luna-Aceves, "A Loop-Free Extended Bellman-Ford Routing Protocol without Bouncing Effect," *ACM Computer Communications Review,* 19(4), 1989, pp.224-236.

[Corson95] M. S. Corson and A. Ephremides, "A Distributed Routing Algorithm for Mobile Wireless Networks," *ACM J. of Wireless Networks,* Jan. 1995, pp.61-81.

[Davies87] B.H. Davies and T.R. Davies, "The application of packet switching techniques to combat net radio," *Proceedings of the IEEE,* vol.75, pp.43-55, January 1987.

[Davis95] R.L. Davis et al, "Ad-Hoc Wireless Networking: Contention Free Multiple Access Using Token Passing," 1995 IEEE 45th Vehicular Technology Conference, Chicago, IL, 25-28 July 1995.

[Dube97] R. Dube, C.D. Rais, K.-Y. Wang, and S.K. Tripathi, "Signal Stability-Based Adaptive Rputing (SSA) for Ad Hoc Mobile Networks," *IEEE Personal Communications Magazine,* February 1997.

[Ephremides87], A. Ephremides, J.E. Eieselthier, and D.J. Baker, "A design concept for reliable mobile radio networks with frequency hopping signaling," *Proceedings of the IEEE,* vol.75, pp.56-73, January 1987.

[Flynn86] M.M. Flynn, C.Spangler, and A. Zimmerman, "The Stanford packet radio network," in Proc. *COMPCON'86,* Spring 1986.

[Fullmer95] C.L. Fullmer and J.J. Garcia-Luna-Aceves, "Floor Acquisition Multiple Access (FAMA) for Packet-Radio Networks," in Proc. of *ACM SIGCOMM'95,* 1995.

[Freebersyser96] J.A. Freebersyser, "Battlefield Applications for Ad Hoc Networking," Panel Session, in Proc. of *Computer Communications Workshop,* 1996.

[Ganz96] A. Ganz, Z.J. Haas, and C.M. Krishna, "Multi-Tier Wireless Networks for PCS," *IEEE Vehicular Technology Conference,* Atlanta, GA, April 29, 1996 - May 1, 1996.

[Garcia-Luna-Aceves85] J.J. Garcia-Luna-Aceves et al, "Analysis of Routing Stategies for Packet Radio Networks," Proceedings of IEEE INFOCOM '85, Washington, DC, 26-28 March 1985.

[Garcia-Luna-Aceves86] J.J. Garcia-Luna-Aceves, "A Fail-Safe Routing Algorithm for Multihop Packet-Radio Networks," Proceedings of *IEEE INFOCOM '86,* Miami, FL, 8-10 April 1986.

[Gerla86] M. Gerla, "Routing and Flow Control in ISDN'd," *ICCC'86,* pp.643-647, 1986.

[Gerla95] M. Gerla and J.T-C. Tsai, "Multicluster, Mobile, Multimedia Radio Network," *ACM/Baltzer Wireless Networks Journal,* vol.1, no.3, pp.255-265 (1995).

[Goodman90] D.J. Goodman, R.A. Valenzuela, K.T. Gayliard, and B. Ramamurthi, "Packet Reservation Multiple Access for Local Wireless Communications," *IEEE Trans. on Comm.,* pp.885-890, August 1990.

[Haas93] Z. Haas and C.-L I, "On Handoffs in Packetized Wireless Systems," *IEEE GLOBECOM'93,* Houston, TX, Nov. 29 - Dec. 2, 1993.

[Haas96-1] Z. J. Haas and C.-P. Li, "The Case for Multiply-Detected Macrodiversity Scheme in Mobile Systems," *IEEE MILCOM'96,* McLean, VA, October 21-24, 1996.

[Haas96-2] Z.J. Haas, J.H. Winters, and D.S. Johnson, "Simulation Results of Cellular Capacity Bounds," accepted for publication in *IEEE Journal on Vehicular Technology.*

[Haas97-1] Z.J. Haas, "The Relaying Capability of the Reconfigurable Wireless Networks," *IEEE VTC'97,* Phoenix, AZ, May 5-7, 1997.

[Haas97-2] Z.J. Haas, "A Routing Protocol for the Reconfigurable Wireless Networks," *IEEE ICUPC'97,* San Diego, CA, October 12-16, 1997.

[Haas97-3] Z.J. Haas and M.R. Pearlman, "Providing Ad-Hoc Connectivity with the Reconfigurable Wireless Networks," submitted to *ACM/Baltzer Journal on Mobile Networks,* special issue of Ad-Hoc Networks.

[Hajek83] B. Hajek, "Adaptive Transmission strategies and routing in mobile radio networks," in Proc. of *17th Conference on Information Science and Systems,* 1983.

[Izumoto93] T. Izumoto et al, "A Self-Organizing Wireless LAN System," Proc. of 18th Conference on Local Area Networks, Minneapolis, MN, 19-22 Sept. 1993.

[Johnson74] Johnson, D.J., "Approximation Algorithms for Combinatorial Problems," *J. of Computer and System Sciences,* vol. 9, pp. 256-278, December 1974.

[Johnson96] D.B. Johnson and D.A. Maltz, "Dynamic Source Routing in Ad-Hoc Wireless Networking," in *Mobile Computing,* T. Imielinski and H. Korth, editors, Kluwer Academic Publishing, 1996.

[Jubin87] J. Jubin and J.D. Tornow, "The DARPA Packet Radio Network Protocols," *Proceedings of the IEEE,* special issue on Packet Radio Networks, vol.75, pp.21-32, Jan. 1987.

[Kahn78] R.E. Kahn *et al.,* "Advances in packet radio technology," *Proceedings of the IEEE,* vol.66, pp.1468-1496, Nov. 1978.

[Kahn77] R.E. Kahn, "The organization of computer resources into a packet radio network, "*IEEE Transactions on Communications,* vol.COM-25, pp.169-178, January 1977.

[Karn85] P.R. Karn, H.E. Price, and R.J. Diersing, "Packet radio in the amateur service," *Journal of Selected Areas in Communications,* vol.SAC-3, pp.431-439, May 1985.

[Karn90] P. Karn, "MACA - a New Channel Access Method for Packet Radio," in *ARRL/CRRL Amateur Radio 9th Computer Networking Conference,* pp.134-140, ARRL, 1990.

[Karol96] M.J. Karol, Z.J. Haas, C.B. Woodworth, "Performance Advantage of Time-Frequency-Sliced Systems," accepted for publication in *IEEE Journal on Vehicular Technology.*

[Kleinrock85] L. Kleinrock and F. A. Tobagi, "Packet switching in radio channels: Part 1 - Carrier sense multiple-access methods and their throughput-delay characteristics," *IEEE Trans. on Comm.,* vol.COM-23, no.12, pp.1400-1416, December 1985.

[Lauer88] G. Lauer, "Address Servers in Hierarchical Networks," IEEE International Conference on Communications '88, Philadelphia, PA, 12-15 June 1988.

[Leiner87-1] B.M. Leiner, D.L. Nielson, and F.A. Tobagi, *Proceedings of the IEEE,* special issue on *Packet radio Networks,* January 1987.

[Leiner87-2] B.M. Leiner, D.L. Nielson, and F.A. Tobagi, "Issues in Packet Radio Network Design," *Proceedings of the IEEE,* vol.75, pp.6-20, January 1987.

[Lin97] C.R. Lin and M. Gerla, "Asynchronous Multimedia Multihop Wireless Networks," *IEEE INFOCOM'97,* Kobe, Japan, 7-11 April, 1997.

[Moy94] J. Moy, "OSPF Version 2], *RFC 1583,* March 1994.

[Murthy] S. Murthy and J.J. Garcia-Luna-Aceves, "An Efficient Routing Protocol for Wireless Networks," to appear in *ACM Wireless Networks* journal, special issue on *Routing in Mobile Communication Networks.*

[Murthy95] S. Murthy and J.J. Garcia-Luna-Aceves, "A Routing Protocol for Packet Radio Networks," Proc. of ACM Mobile Computing and Networking Conference, *MOBICOM'95,* Nov. 14-15, 1995.

[Perkins94] C. E. Perkins and P. Bhagwat, "Highly Dynamic Destination-Sequenced Distance-Vector Routing (DSDV) for Mobile Computers," *ACM SIGCOMM,* vol.24, no.4, Oct. 1994, pp.234-244.

[Perkins96-1] C.E. Perkins, "Mobile-IP, ad-hoc networking, and nomadicity," in Proc. *COMPSAC'96.*

[Perkins96-2] C. Perkins, editor, "IP Mobility Support," Internet Engineering Task Force, Internet Drafts, draft-ietf-mobileip-protocol-15.txt, Feb. 9, 1996.

[Pollini94] G. Pollini and Z. Haas, "A Comparison of Beacon-Assisted Multiple Access and Resource Auction Multiple Access," *IEEE Network,* March/April 1994, pp. 18 - 25.

[Pursley96-1] M.B. Pursely, "Investigation of least resistance routing in a mobile SINCGARS packet radio network," Proc. of the *1996 Tactical Communications Conference,* Fort Wayne, IN, April 30 – May 2, 1996.

[Pursley96-2] M.B. Pursely, "Measuring the link qualities in a frequency-hop packet radio network for use in the routing of multimedia packets," Proc. of the *1996 Tactical Communications Conference,* Fort Wayne, IN, April 30 – May 2, 1996.

[Pursely93] M.B. Pursely, "Routing in frequency-hop packet radio networks with partial-band jamming," *IEEE Transactions on Communications,* vol.41, no.7, July 1993.

[Scott95] K. Scott and N. Bambos, ``The Self-Organizing Wireless Network (SWAN) Protocol for Communication Among Mobile Users," in Proceedings of *Globecom'95,* Singapore, Nov. 13-17, 1995, pp. 355-359.

[Shacham83] N. Shacham, E.J. Craighill, and A.A. Poggio, "Speech Transport in Packet-Radio Networks with Mobile Nodes," *IEEE J. on Selec. Areas in Comm.,* pp.1084-1097, Dec. 1983.

[Shacham87] N. Shacham and J. Westcott, "Future Directions in Packet Radio Architectures and Protocols," in *Proceedings of the IEEE,* vol.75, pp.83-99, January 1987.

[Sharony96] J. Sharony, ``A Mobile Radio Network Architecture with Dynamically Changing Topology Using Virtual Subnets," *MONET,* vol.1, no.1, pp.75-86. Also in Proceedings of *ICC/SUPERCOM'96,* Dallas, TX, June 23-27, 1996, pp.807-812.

[Shor93] J. Shor and T.G. Robertazzi, "Traffic Sensitive Algorithms for generating Self-Organizing Radio Network Schedules," IEEE Transactions on Communications, vol.41, no.1, p. 16-21, January 1993.

[Tobagi85] F. A. Tobagi and L. Kleinrock, "Packet switching in radio channels: Part 2 - The hidden terminal problem in carrier sense multiple-access and the busy tone solution, *IEEE Trans. on Comm.,* vol.COM-23, no.12, pp.1417-1433, December 1985.

[Tobagi78] F. A. Tobagi, M. Gerla, R.W. Peebles, and E.G. Manning, "Modeling and Measurement Techniques in Packet Communication Networks," *Proceedings of the IEEE,* vol.66, no.11, pp.1423-1447, November 1978.

[Toh97] C.-K. Toh, "Wireless ATM and Ad-Hoc Networks," *Kluwer Academic Publishers,* 1997.

7.0 Glossary of Acronyms and Notation

dB - decibel
kbps – kilobit per second
m - meter
sec - second
DARPA – Defense Advanced Research Projects Agency
DBF – Distributed Bellman-Ford
ET – Early Termination
HLR – Home Location Registry
IARP – IntrAzone Routing Protocol
IERP – IntErzone Routing Protocol
IP – Internet Protocol
ID – IDentifier
IETF – Internet Engineering Task Force
LP – Loop-back Termination
Mbps – Megabit per second
MAC – Medium Access Control
MEMS – Micro Electro-Mechanical Systems
MSC – Mobile Switching Center
OPNET™ – OPtimized Network Engineering Tools
PL – Path Loss
PRNET – Packet Radio NETwork
QD1 – Query Detection 1
QD2 – Query Detection 2
RWN – Reconfigurable Wireless Networks
SBC – Selective BorderCasting
VLR – Visitor Location Registry
WRP – Wireless Radio Protocol
ZRP – Zone Routing Protocol

ρ *- Zone Radius*
θ *- angle of mobile's velocity*
v *- mobile's velocity*
d *– distance between two mobiles*
d_{xmit} *- maximum nodal transmission distance*

MISSION
OF
AFRL/INFORMATION DIRECTORATE (IF)

The advancement and application of information systems science and technology for aerospace command and control and its transition to air, space, and ground systems to meet customer needs in the areas of Global Awareness, Dynamic Planning and Execution, and Global Information Exchange is the focus of this AFRL organization. The directorate's areas of investigation include a broad spectrum of information and fusion, communication, collaborative environment and modeling and simulation, defensive information warfare, and intelligent information systems technologies.